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EVALUATION OF FLUSH MOUNTED HOT-FILM SENSORS FOR SKIN FRICTION REDUCTION MEASUREMENTS IN VISCOELASTIC POLYMER SOLUTIONS

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EVALUATION OF FLUSH MOUNTED HOT-FILM SENSORS FOR SKIN FRICTION REDUCTION
MEASUREMENTS IN VISCOELASTIC POLYMER SOLUTIONS

W. L. Harbison and H. L. Petrie

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From: W. L. Harbison and H. L. Petrie

Subject: *Evaluation of Flush Mounted Hot-Film Sensors for Skin Friction*
                Reduction Measurements in Viscoelastic Polymer Solutions

References: See Page 16.

Abstract: The performance of flush mounted hot-film sensors for mean wall
                shear stress measurement in turbulent flows of dilute drag
                reducing polymer solution is evaluated. A series of pipe flow
                experiments were conducted to compare the level of skin friction
                reduction measured by hot-film sensors with values determined from
                the pipe pressure drop. Water calibrated hot-film sensors
                consistently underestimate the wall shear stress in the dilute
                polymer flows. For the range of flows tested, hot-film determined
                percent drag reductions are low but generally within 15 percent of
                the correct value. Like drag reduction, heat transfer reduction
                results from the elastic properties of polymer solutions. These
                two phenomena are distinct and their differences suggest that
                Reynolds' analogy is not valid in dilute polymer flows.

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NOMENCLATURE

A	-	Slope of the hot-film calibration curve, Equation 3.
ΔA	-	Change in the calibration slope due to polymer.
B	-	Offset of the hot-film calibration curve, Equation 3.
ΔB	-	Change in the calibration offset due to polymer.
D	-	Inside diameter of the test pipe.
E_{HF}	-	Voltage across the hot-film.
f	-	Darcy friction factor, Equation 16.
h	-	Convective heat transfer coefficient.
k	-	Conduction heat transfer coefficient.
L or L_p	-	Length of the test pipe between pressure taps.
Δp	-	Static pressure difference between pressure taps.
$\dot{q}$	-	Heat transfer rate.
R	-	Electrical resistance of the hot-film.
Re_D	-	Reynolds number in test pipe based on pipe diameter.
ΔT	-	Temperature difference between hot-film and ambient.
$\bar{V}$	-	Bulk or mean velocity in the test pipe.
x	-	A length.
x_e	-	Entry or exit length of the test pipe.
τ_w	-	Shear stress at the wall of the pipe.
—	-	Overbar indicates a mean quantity.

Subscripts

TTWL	-	Theoretical Turbulent Water Line, Figure (2) and Equation 7.
TLWL	-	Theoretical Laminar Water Line, Figure (2).
MDRA	-	Maximum Drag Reduction Asymptote for Pipe Flow, Figure (2).

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INTRODUCTION

In addition to small amounts of soluble long chain polymers to water yields solutions which exhibit significant skin friction reduction in wall bounded turbulent shear flow. Polymer drag reduction in internal and external turbulent flows have been studied extensively and review articles discussing polymer additives, their effects on the flow and applications are presented by White and Hemmings [1976], Berman [1978], Sellin, Hoyt and Scrivener [1982] and Sellin, Hoyt, Pollert and Scrivener [1982]. In external flows, polymer solutions are typically introduced in the near wall region of a turbulent boundary layer (TBL) through narrow inclined slots, see Wu and Tulin [1972] or Walker, Tiederman and Luchik [1986]. An important aspect of the external flow problem involves the mixing and dilution of the polymer solution downstream of the injection slot and the subsequent effect on drag reduction. Drag reduction is quantified by measuring the decrease in wall shear stress caused by the introduction of polymer into a flow with a fixed mass flow rate. In order to carry out model studies of this phenomena in an external flat plate flow with slot injected polymer, it would be extremely useful to be able to make reliable measurements of local wall shear stress. This was motivation for evaluating the performance of surface flush mounted hot-film anemometers in flows of polymer solution.

The use of flush mounted hot-film sensors for the measurement of turbulent wall shear stress was pioneered by Ludwieg [1950] whose paper presents a detailed analysis of the underlying theory. A sensor consists of a thin platinum film sputtered onto a non-conducting substrate. For use in liquids, the film is covered by a thin quartz coating. An electronic bridge circuit is used to heat the film and hold it at a constant temperature above that of the fluid. A heat balance for the hot-film sensor takes the form:

$$\dot{q} = \frac{E_{HF}^2}{R} = (h + k)\Delta T \tag{1}$$

where the left hand term (E_{HF}^2/R) is the power, supplied by the bridge circuit, required to maintain the constant temperature difference ΔT, also called the overheat. The term $h\Delta T$ represents the convective heat transfer to the fluid while $k\Delta T$ represents conduction to the substrate. The hot-film sensor measures heat transfer directly. The relationship between heat transfer, $\dot{q}$, and wall shear stress, τ_ω, was shown by Liepmann and Skinner [1954] to be:

$$\tau_\omega^{1/3} \quad \alpha \quad \dot{q}$$

or

$$\tau_\omega^{1/3} = AE_{HF}^2 + B \tag{2}$$

where E_{HF} is the measured bridge voltage, and A and B are constants. In practice, the coefficients A and B are determined using mean shear stress and bridge voltage values attained from a calibration in a standard flow, one in

which the relationship for the wall shear stress is known (e.g. pipe or zero pressure gradient flat plate TBL flows), or from a device which measures wall shear stress directly, such as a "floating" balance. In the present work, the form of Equation (2) used was:

$$\overline{\tau_\omega}^{1/3} = A\overline{E_{HF}^2} + B \tag{3}$$

for all calibrations. The overbar denotes a time average.

After the coefficients A and B are determined, bridge voltage measurements can be converted directly to shear stress measurements. The theory assumes that the hot-film establishes a linear thermal boundary layer which is thinner than the viscous sublayer over the length of the film [Liepmann and Skinner 1954]. This assumption may place limits on the length of the film or the speed of flow tested; however, a successful linear calibration across the speed range of interest is sufficient to eliminate this concern. Problems can arise if a hot-film is used to test outside its calibration range or if the calibration is done with a fluid other than the solution being tested. This is due to the highly nonlinear relationship between the wall shear stress and bridge voltage which amplifies the effects of deviations from the calibration relationship.

The rheology of dilute polymer solutions is almost indistinguishable from water; therefore, it may seem reasonable to assume that hot-film sensors can be calibrated in water to make wall shear stress measurements in dilute polymer solutions. Calibration in water is desirable because it allows the use of the theoretical and empirical water equations available for various standard geometry flows, such as zero pressure gradient flat plate TBL flow. To determine if the assumption is correct, the sensors must be tested in a polymer flow where the value of wall shear stress can be established independently of the sensors.

A recent study of Goforth et al. [1987] mounted hot-film sensors on the surface of a rotating disk submerged in a polymer solution of 100 weight parts per million (wppm) Separan AP-30. The surface shear stress was measured by the sensors and compared to a value derived from a torque measurement on the disk. The investigators reported considerable scatter in the data due to the indirect method used to make torque measurements and the noisy electrical slip rings used in the sensor circuits. Despite the scatter, the drag reduction measurements made by the sensors were found to be 25 to 45 percent larger than those based on the torque measurements. The discrepancy was caused by a decrease in heat transfer between the sensors and the Separan solution. This decrease was blamed on a thin coating of polymer which insulates the films. The investigators concluded that: (1) accurate wall shear stress measurements in polymer solutions could not be made by flush mounted hot-film sensors which are calibrated in water, (2) sensor calibrations in dilute polymer solutions are possible and remain stable with time, and (3) the performance of hot-film sensors in pure water are not affected by prior immersion of the sensors in dilute polymer solutions. Based on these conclusions, the investigators suggested that it might be possible to determine a functional relationship between the calibration constants of a sensor in water and its calibration constants in dilute polymer solutions.

In order to avoid some of the difficulties encountered by Goforth et al. [1987], a different set-up was used for the present investigation. The special geometry of pipe flow allows mean wall shear stress to be calculated directly from the average pressure drop along the length of a pipe. By propelling a steady flow of polymer solution through a pipe which has hot-film sensors mounted flush on its inner surface, the mean drag reduction calculated from sensor wall shear stress measurements can be compared directly with the mean drag reduction calculated from pipe pressure drop. In this manner, the accuracy of the hot-film sensors in making skin friction reduction measurements in turbulent flows of drag reducing polymer solution can be determined.

EXPERIMENTAL APPARATUS AND PROCEDURES

The pipe flow facility used for these experiments is shown in Figure (1). The pipe is made of seamless stainless steel tubing and has an inside diameter (D) of 10.8 mm. Pipe diameter was chosen so the facility would provide a range of Reynolds number flows in the turbulent regime ($10,000 < ReD < 100,000$). The effective test section of the pipe, where measurements are made, is the length between the two static pressure tap locations ($L = 3.054$ m, $L/D = 283$). The entrance and exit lengths of the test pipe (x_e) are 54.3 cm ($x_e/D = 50.3$). The inlet end of the test pipe was joined to the upstream flow valve and the discharge tank by sections of 9.5 mm I.D. polyvinyl tubing. The total length of the connection between the discharge tank and the inlet end of the test pipe was 64.5 cm which brings the total entry length for the pipe flow facility (x_e) to 118.8 cm ($x/D = 110$). The entry length required for fully developed turbulent pipe flow with water can be estimated using the equation from White [1979]:

$$\frac{x_e}{D} \approx 4.4\ Re_{D^{1/6}}$$ (4)

where Re_D is Reynolds number based on pipe diameter. For turbulent pipe flow with water in the Reynolds number range mentioned above, the ratio (x/D) must exceed 30.0 to satisfy the entrance length requirement. For concentrated polymer solutions, Yoo [1974] measured a required hydrodynamic entry length of $x/D = 80$ for fully developed turbulent flow. In a different study, Tung et al. [1978] reported an entry length of $x/D = 100$ for a 2000 weight parts per million (wppm) Separan solution. Based on these findings, the entry length in the present facility should assure a fully developed turbulent profile in the test section for both water and dilute polymer solutions.

The facility operates as a "once through" system and uses a pressurized discharge tank to drive the flow. This configuration prevents polymer degradation which may occur in a "loop" system or in a facility which uses a mechanical pump. The test fluid is loaded into the discharge tank which is then pressurized with air. The pipe control valves are opened, and the fluid flows through the pipe and into the collection tank. A constant pressure is maintained in the discharge tank, during a run, by the air regulator valve. The collection tank is suspended from a rigid wall mounted beam on a strain gage sensor that determines the weight of the collection tank and its contents

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continuously. During a test run, the derivative of the tank weight with respect to time is used to determine the mass flow rate and therefore, the bulk velocity and Reynolds number in the pipe. Since the mass flow rate is held constant, the tank weight increases linearly with time and a linear least squares curve fit was used to determine these values.

The instrumentation pods, shown in Figure (1), hold the pressure taps and the plugs on which the hot-film sensors are mounted. The pipe flow pressure drop is measured between the two static taps using a differential pressure transducer. To insure that the insertion end of each plug has the same radius as the pipe, the plugs were mounted on the instrumentation pods and both pieces were cut to the final radius together. The plug is pinned for proper alignment and features an O-ring to prevent leakage. The removal of the plug allows easy access to the epoxy mounted hot-film sensor.

The hot-film sensors are controlled by a constant temperature bridge. The standard bridge circuit of a TSI IFA-100 anemometer system was used. The overheat ratio was set to 3 percent. The bridge voltage was digitized with a TSI IFA-200 analog to digital converter. This system also digitized the output of the differential pressure transducer and the collector tank strain gage bridge. A PC-AT computer was used for instrumentation control and data sampling. For further details on the experimental apparatus and procedures, see Harbison [1990].

Four channels of data were collected during a run: the collection tank strain gage voltage, the pipe pressure drop voltage and two hot-film bridge voltages. All channels were sampled at 50 Hertz for a period of 20 seconds during a run. The mean wall shear stress is calculated from the mean pipe pressure drop ($\overline{\Delta P}$) using the relationship:

$$\overline{\tau_\omega} = \frac{D\overline{\Delta P}}{4 L_p} \tag{5}$$

where D is pipe inside diameter and L_p is the pipe length between the pressure taps. This pressure drop value is used to calibrate the hot-film sensors in water or to compare with the hot-film results during data analysis in polymer flows. A series of calibration runs with water were performed before and after each set of data gathering runs. The calibration set is used to specify the relationship between the wall shear stress and the hot-film sensor bridge voltage for the bracketed data trial. A water trial was conducted before each polymer trial to check the performance of the hot-film sensors before polymer testing.

The polymer used for this investigation was commercial grade Separan AP-30 manufactured by the Dow Chemical Company. Test solutions were homogeneous mixtures of Separan in tap water at various concentrations ranging from 5 to 500 weight parts per million (wppm). The mixing of solutions consisted of sprinkling the Separan flakes onto the surface of the water while stirring gently. The mixtures were allowed to stand for about 18 hours, with intermittent stirring, to insure the solution was well hydrated. The tests were always carried out within a day of mixing. All fluids run in the

facility were allowed to come to room temperature (23° C) before the test began. Fluid temperatures were monitored and never varied by more than 0.5° C during a single test.

In general, the properties of aqueous solutions of drag-reducing polymers, other than viscous and elastic properties, have been taken to be the same as water. This practice was justified by Yoo [1974] who measured the physical properties of various drag-reducing polymer over a range of concentrations and temperatures. Values for thermal conductivity, density and specific heat measured for 1000 wppm Separan AP-30 at room temperature, taken from Yoo [1974], are shown in Table 1. No significant differences in the properties with the values for water are observed. For the present experiment, Reynolds number based on the estimate shear viscosity at the wall was used. The viscosities of the test solutions were measured in a cone and plate viscometer. For Separan concentration less than 50 wppm, the viscosity is constant and does not differ significantly from the value for water (.94 cps @ 23° C). For the higher concentrations, the solutions were shear thinning and the viscosity approached a constant value with increased shear rates.

EXPERIMENTAL RESULTS

The only difficulty encountered during the testing was the failure of the hot-film sensor in the upstream pod (i.e. hot-film #1). The sensor in this location survived four tests. The downstream sensor (i.e. hot-film #2) operated flawlessly throughout the experiment. As a result, data from hot-film #1 is only available at four Separan concentrations.

The water trial Darcy friction factors calculated from the pipe pressure drop are shown in Figure (2). The Darcy friction factor [White 1979] is defined as:

$$f = \frac{8\,\overline{\tau_\omega}}{\rho\,\overline{V}^2} \tag{6}$$

where $\overline{\tau_\omega}$ is the measured mean pipe wall shear stress, $\overline{V}$ is the measured mean flow velocity and ρ is the fluid density. The theoretical smooth pipe relationships for water flow are represented by the lines on Figure (2). The Theoretical Turbulent Water Line (TTWL), estimated by the equation from White [1979]:

$$\frac{1}{f_{TTWL}^{1/2}} = 2.0\,\log(Re_D\,f_{TTWL}^{1/2}) - 0.8$$

where Re_D is the Reynolds number based on pipe diameter, represents fully developed turbulent water flow in the pipe. The water flow friction factors calculated from the pipe pressure drop agree with this relationship within ± 7.5 percent scatter. Friction velocities for the range of water flows tested fall between 0.07 and 0.27 m/sec.

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The friction factors measured by the water calibrated hot-film sensors in water as a check prior to each polymer experiment are in good agreement with the pressure drop values. The amount of scatter inherent in the measurement of wall shear stress for the hot-film sensors compared with the pressure drop values is approximately ± 10 percent and is shown as a ratio over a range of Reynolds numbers in Figure (3). The scatter, between the individual measurements, may result from factors such as sensor drift and the build-up of sensor surface contaminants over time. Surface contaminants affect the heat transfer properties of the hot-films. Due to the highly non-linear relationship between bridge voltage and wall shear stress ($\tau_W \alpha E_{HF}^6$) sensor drift or small variations in heat transfer can lead to significant scatter between measurements.

The performance of hot-film sensors in water is not affected by their prior use in dilute polymer solutions. Even after repeated immersion in polymer solutions, the sensors completely recovered their heat transfer ability immediately when re-calibrated in water. The same behavior was noted by Goforth et al. [1987].

The addition of polymer to a pipe flow tends to decrease pipe wall shear stress; consequently, some of the measurements which can be made in polymer flows at low Reynolds numbers fall below the range established by the water calibration. As a result, approximately 20 percent of the wall shear stress measurements were made outside their respective calibration ranges. As expected, the problem occurs chiefly at high Separan concentrations and low Reynolds number. Nevertheless, these measurements are included here and are considered correct on the basis of the strong linear nature of the calibration curves and the consistency of the data trends.

The average level of drag reduction measured in the pipe by the downstream sensor (hot-film #2) along with the correct level, calculated from pipe pressure drop, are presented in Figure (4). The limited data from the upstream sensor (hot-film #1) is nearly identical. This agreement supports the claim of fully developed turbulent pipe flow with polymer solutions. Drag reduction is quantified by measuring the percent decrease in wall shear stress caused by the introduction of polymer into a pure water flow. The figure shows the percent drag reduction for turbulent flows of Separan solution with respect to pure water flow at the same mass flow rate. In order to compare the percent drag reduction for different Separan concentrations at the same Reynolds number, the values plotted in Figures (4) and (5) have been interpolated from the raw data for each Separan concentration, using a linear least squares fit between percent drag reduction and the logarithm of Reynolds number. The solid symbols in Figure (4) represent the actual drag reduction calculated from pipe pressure drop (ΔP measurements). The maximum drag reduction levels, based on pipe pressure drop, measure approximately 70 percent and agree very well with Virk's et al. [1970] maximum drag reduction asymptote. This asymptotic condition is attained at Re_D – 20,000 at 50 wppm and at $Re_D > 60,000$ at 200 wppm concentrations. The open symbols represent the drag reduction measured by the hot-film sensors (H.F. measurements). Note that the hot-film sensor overestimates drag reduction at all Separan concentrations tested. Maximum errors in drag reduction are always less than 20 percent and generally less than 15 percent. Drag reduction exceeding

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Virk's maximum are measured by the water calibrated hot-films for concentrations of 50 wppm or more.

The error in the measurement of drag reduction for hot-film sensor #2, as a function of Reynolds number, at different Separan concentrations is shown in Figure (5). A jump in the error occurs at a concentration of 10 wppm. At concentrations greater than 100 wppm, the error seems to approach a constant value of approximately 14 percent. The results seen in Figures (4) and (5) reflect the tendency of the water calibrated hot-film sensors to measure deceptively low values of wall shear stress in dilute polymer solutions.

DISCUSSION OF EXPERIMENTAL RESULTS

The over-prediction of drag reduction in turbulent flows of dilute polymer solution of flush mounted hot-film sensors results from a decrease in heat transfer between the sensor and the polymer solution beyond the decrease which is directly attributable to drag reduction alone. As a result, the relationship, established from the water calibration, between wall shear stress and sensor heat flux becomes inaccurate in dilute polymer flows. Therefore, it becomes necessary to determine what relationship, if any, exits between these variables in turbulent flows of Separan solution.

To determine if a calibration relationship of the form given by Equation 3, with the mean shear stress based on the measured pressure drop, remains valid for dilute polymer flows, data gathered in the polymer trials were re-plotted in the form of calibration curves. An example of the resulting curves for hot-film #2 at four polymer concentrations is shown in Figure (6). The linearity of these polymer hot-film calibration curves confirms that the form of the relationship remains valid, only the coefficients A and B need to be modified to account for the variations in heat transfer. It is not strictly valid to compare the calibration curves on the basis of changing concentration because small differences in fluid temperature, sensor contamination, heat conduction to the sensor substrate and possibly other factors may vary slightly from day to day. In general; however, the curves show some interesting trends. Note that the polymer calibration curves tend to move to the left as concentration increases. This shift represents the general decrease in heat transfer between the sensors and the fluid. The slope of the calibration curves tend to increase as concentration increases and the range of values of the mean bridge voltage squared decreases substantially. This represents the effect of the change in the relationship between sensor heat transfer and Reynolds number as Separan concentrations increase. The conjunction of these effects, in Figure (6), leads to a decrease in hot-film sensitivity with increasing polymer concentration.

In terms of practical results, this means that hot-film sensors can be used to make accurate wall shear stress measurements in homogeneous dilute polymer solutions if they are calibrated in an dentical solution of the same concentration. This conclusion presumes the decrease in sensitivity, at the concentration of interest, is not so severe as to make the measurements unreliable. To make consistent measurements in water, hot-film sensors must

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be calibrated often to account for temperature changes and other calibration shifts. The same principle applies to sensor calibration in dilute polymer solutions. For a series of tests at different homogeneous concentrations, a separate calibration will be necessary for each solution. Such a procedure would be very troublesome and require large amounts of polymer solution.

In an attempt to address this problem, a relationship between polymer concentration and the change in calibration coefficients, from water calibration values, has been found for the present experimental set-up. The change in slope, A, and Y-intercept, B, from the calibration water values for Equation 3, as a function of Separan AP-30 concentration, is shown for hot-film #2 in Figures (7) and (8).

The first step in using these relationships would be to perform a water calibration to determine slope and Y-intercept. After these values are found, they can be modified using the appropriate correction equations if the polymer concentration is known locally at the wall. The water calibration accounts for the temperature and sensor drift, while the correction equations account for the reduction in heat transfer between the sensor and solution over a continuous range of polymer concentrations. The relationships presented in Figure (7) and (8) can be used to predict hot-film sensor measurements of mean wall shear stress within 15 percent of the values calculated from pipe pressure drop. This translates into a maximum discrepancy of 6 percent when the results are reported as the difference in percent drag reduction. These relationships are valid over the range of Separan concentrations and Reynolds numbers tested.

The correction equations would have to be determined separately for each sensor over the concentration range of interest. Calibration in solutions of three or four concentrations should be sufficient to establish the correction. Unfortunately, polymer drag reduction is an unknown function of flow geometry which means the correction equations would probably have to be determined from in situ polymer calibrations. In other words, it is probably not possible to use a hot-film correction determined in one experimental set-up to correct the same sensor when it is moved to a different facility. No general theory for predicting wall shear stress in polymer flow exists, so the calibration procedure will require an independent means of measuring this value. In short, one needs to know the mean wall shear stress - in order to calibrate the hot-film sensors -in order to measure the mean wall shear stress. This redundancy undermines the utility of hot-films for measuring average wall shear stress; however, the procedure may prove useful in applications where the special capabilities of hot-film sensors are required. This includes situations where localized wall shear stress measurements are desired or where fluctuating components of stress are of interest.

The source of the difficulties associated with the use of hot-film sensors in dilute polymer solutions is an excessive decrease in the ability of the sensors to transfer heat to the test solutions as polymer concentration increases. Heat transfer reduction between the sensor and fluid is apparent in very dilute polymer solutions and increases rapidly with increasing concentration. Since there is essentially no difference in viscous or thermal

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properties between water and dilute polymer solutions, these variations in heat transfer result from other properties of the fluid.

The jump in heat transfer reduction for Separan concentrations between 5 and 10 wppm is especially remarkable: not only is there a large drop in heat transfer between the sensor and fluid but also a shift to a new relationship between heat transfer and Reynolds number. Concurrent with this change in heat transfer is a large increase in drag reduction. Clearly, such behavior represents an abrupt transition from a water-like flow at 5 wppm to a stable turbulent polymer flow, with a different flow structure, at 10 wppm. As polymer concentration increases beyond 10 wppm, heat transfer continues to decrease. At a concentration of 100 wppm, heat transfer between the sensor and solution becomes fairly insensitive to further increases in polymer concentration; however, a change in the relationship between heat transfer and Reynolds number was noted at a concentration of 500 wppm.

Several investigators [Kalashnikov and Kudin 1973; Goforth et al. 1987] have implied that the heat transfer reduction between hot-film sensors and dilute polymer solutions is caused by a thin coating of polymer which insulates the films. This theory is not supported by the results of the present experiment. The stability of the wall shear stress measurements and the insensitivity of the sensors to prior immersion in polymer solution suggests there is no coating build-up. If such a coating did exist, the heat transfer would be expected to increase with Reynolds number rather than decrease, on the presumption that the higher pipe wall shear rates would tend to scrub away polymer accumulation. In addition, since the thermal conductivity of dilute polymer solutions equals the value for water, a polymer coating over the sensor would have no more effect on heat transfer than a layer of water. This argument is supported by the investigation of Cho and Hartnett [1982] who carried out heat transfer experiments in a 9.8 mm diameter pipe whose outer wall was heated for a length sufficient to establish a fully developed thermal boundary layer. They found an increase in heat transfer for concentrated polymer solutions of Separan AP-273 in laminar pipe flow: the increase was due to the shear thinning properties of the solution. It is difficult to imagine a coating which forms in turbulent flow but does not form in laminar flow. This suggests that the heat transfer reduction phenomena, encountered in turbulent flow, is a consequence of a change in the structure of the flow rather than an insular coating.

CONCLUSIONS

This study has shown that hot-film sensor measurements of wall shear stress in turbulent flows of dilute polymer solution, based on water calibration, are less accurate than measurements made in pure water flows. The sensors always underestimate the wall shear stress; consequently, they over predict the level of drag reduction achieved by the polymer additive. The measurement of percent drag reduction is generally within 15 percent of the correct value. The actual magnitude of the discrepancy depends on local polymer concentration and Reynolds number.

Hot-film sensors can make accurate measurements in homogeneous polymer solutions if they are calibrated in an identical solution of the same concentration. The technique could be implemented for polymer ocean experiments, or possibly for injection experiments if the polymer concentration is known locally at the wall. In addition, a relationship has been proposed between the calibration constants for a sensor in water and the calibration constants for the same sensor in dilute polymer solution: the relationship is a function of polymer concentration.

Hot-film sensors in turbulent flows of dilute polymer solution exhibit reduced heat transfer and sensitivity. Heat transfer reduction and drag reduction result from the interaction of the turbulent flow structure with the elastic properties of polymer solution. It is obvious that heat transfer reduction is closely linked to drag reduction; however, it appears that the two phenomena are distinct. This fact suggests that a breakdown in Reynolds' analogy occurs in the turbulent flows of dilute polymer solution.

The difficulties associated with the use of hot-film sensors in polymer solution stem from a fundamental lack of understanding about the nature of viscoelastic solutions and how such fluids behave in turbulent flow.

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TABLE 1

	WATER	1000 WPPM SEPARAN AP-30
Thermal Condition	.605 W/m°K	.609 W/m°K
Specific Heat	4.180 kJ/kg°K	4.180 kJ/kg°K
Density	1.0000 g/cm^3	1.009 g/cm^3

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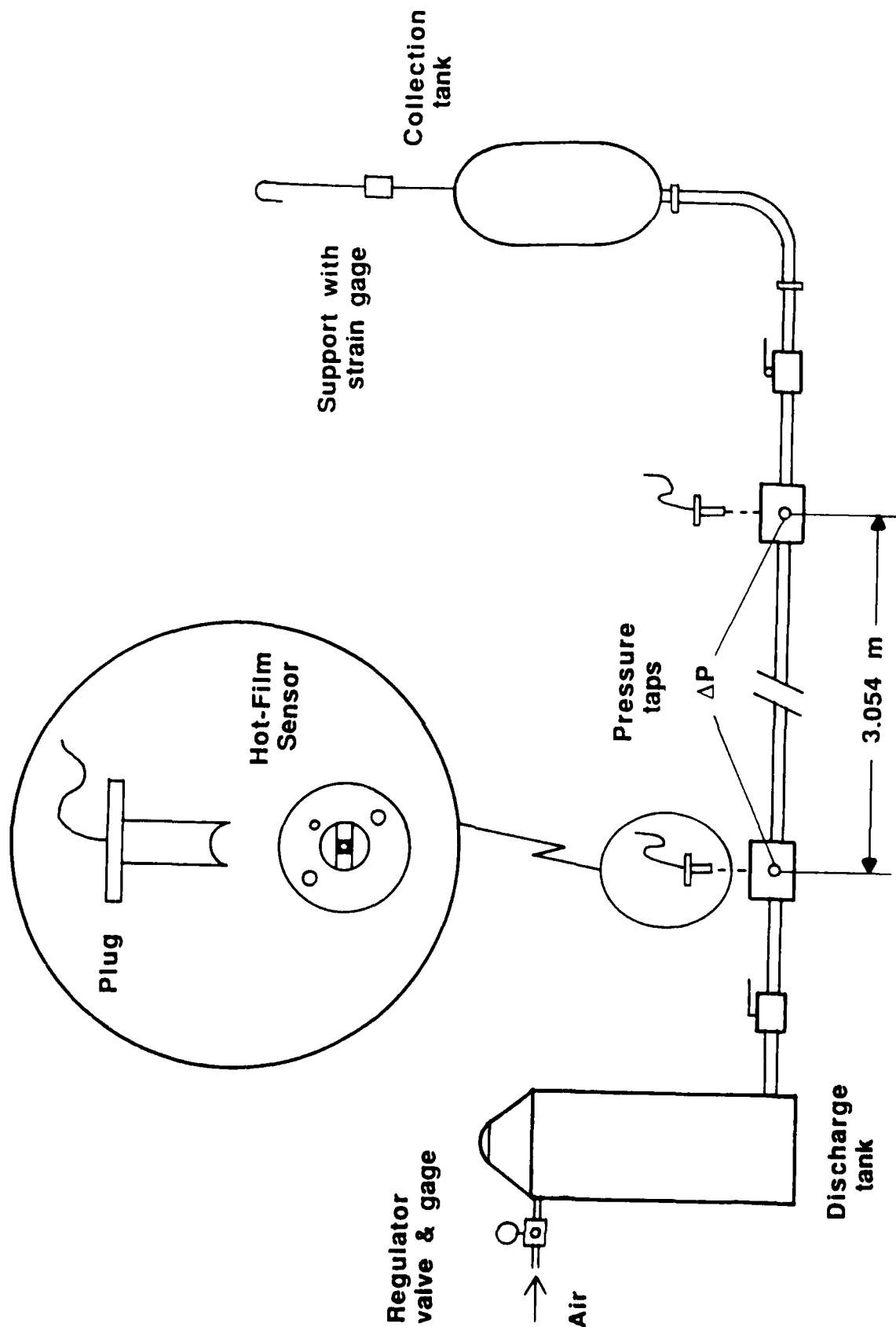
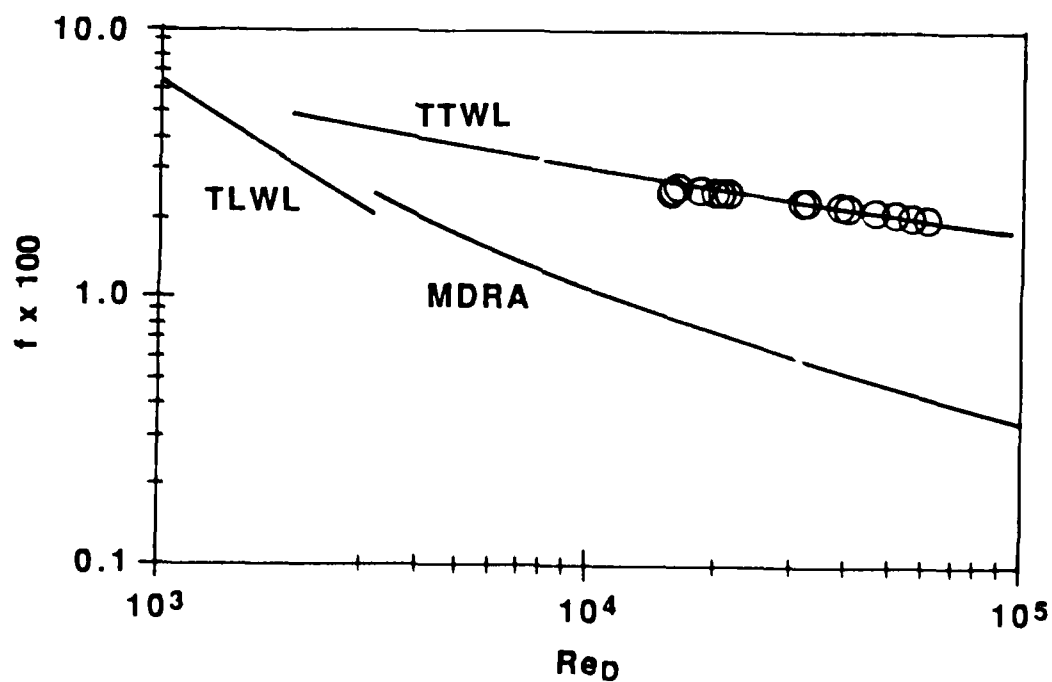Figure 1. Pipe Flow Facility Component Diagram.

Figure 2. Moody Chart With Pressure Drop Determined Friction Factors Compared with the Theoretical Turbulent Water Line (TTWL). The Theoretical Laminar Water Line (TLWL) and Maximum Drag Reduction Asymptote (MDRA) Also Shown.
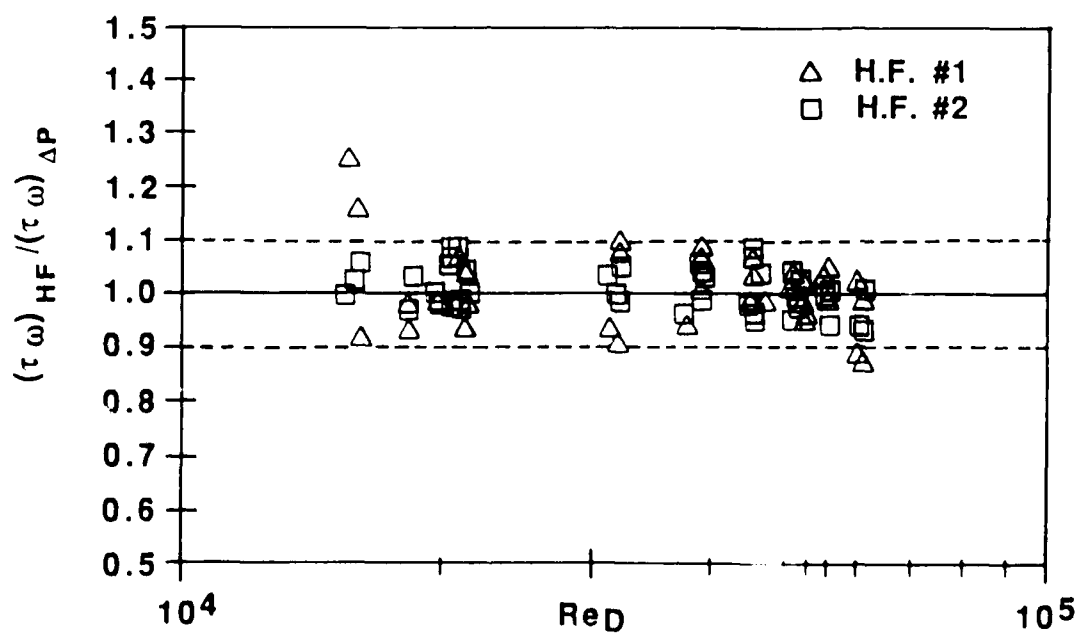
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Figure 3. Comparison of Hot-Film to Pressure Drop Determined Mean Wall Shear Stresses in Water.
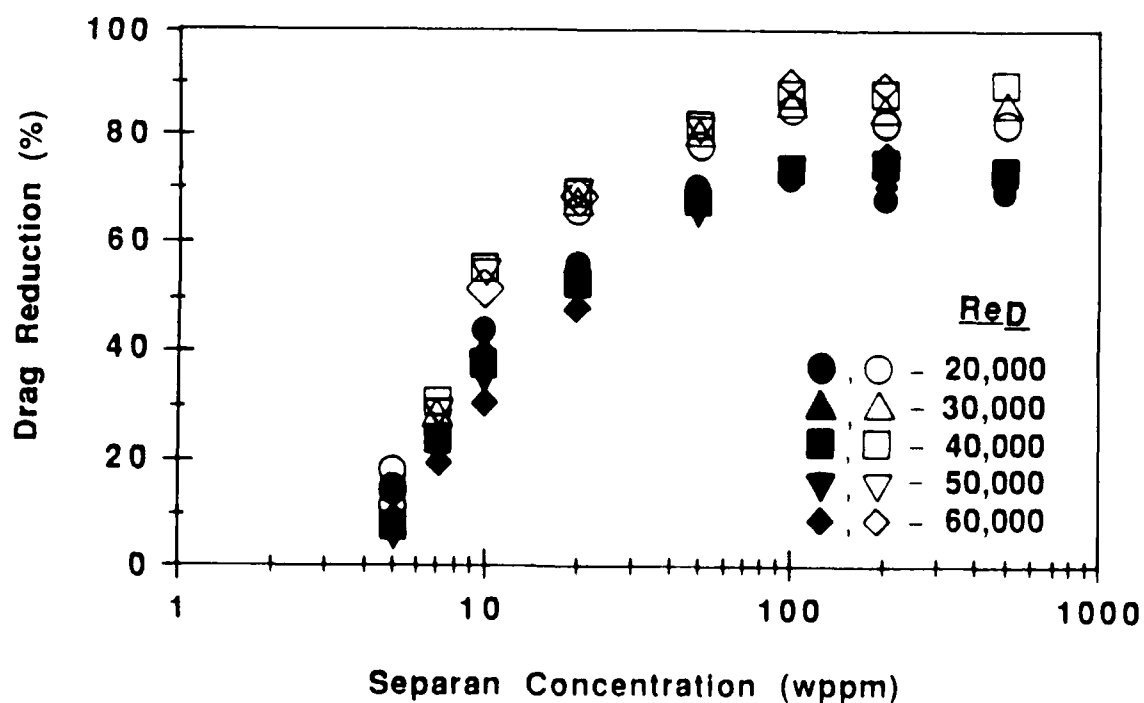
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Figure 4. Variation of the Measured Drag Reduction With Separan AP-30
Concentration for a Range of Reynolds Numbers. Open Symbols -
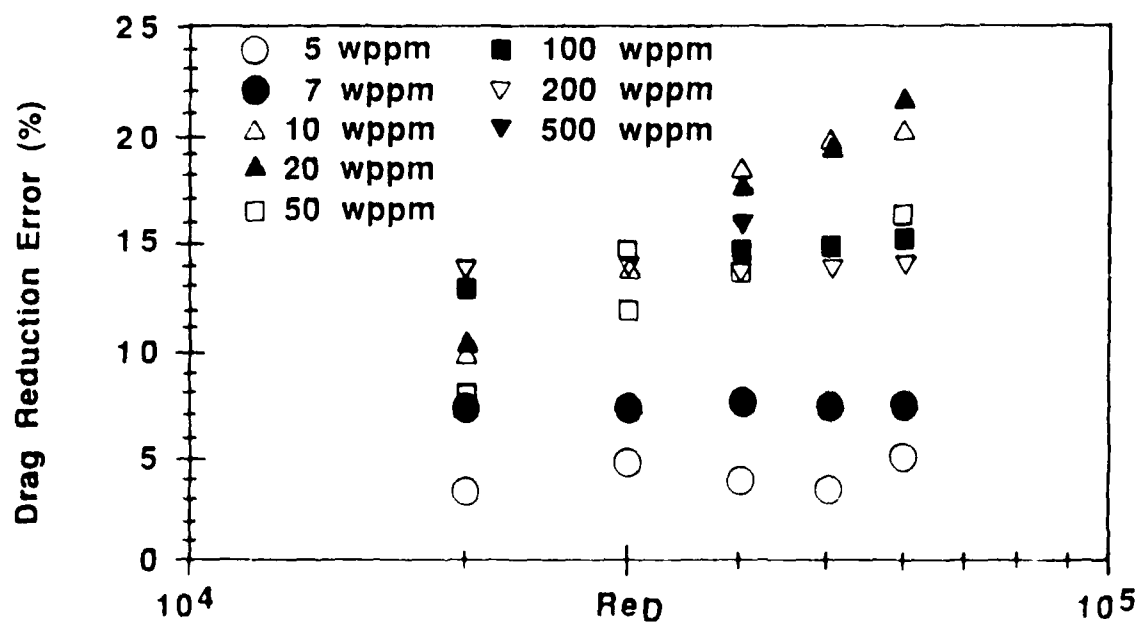Downstream Hot-Film; Closed Symbols Pressure Drop Data.

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Figure 5. Hot-Film Drag Reduction Measurement Error Versus Reynolds Number for All Separan Concentration Considered.

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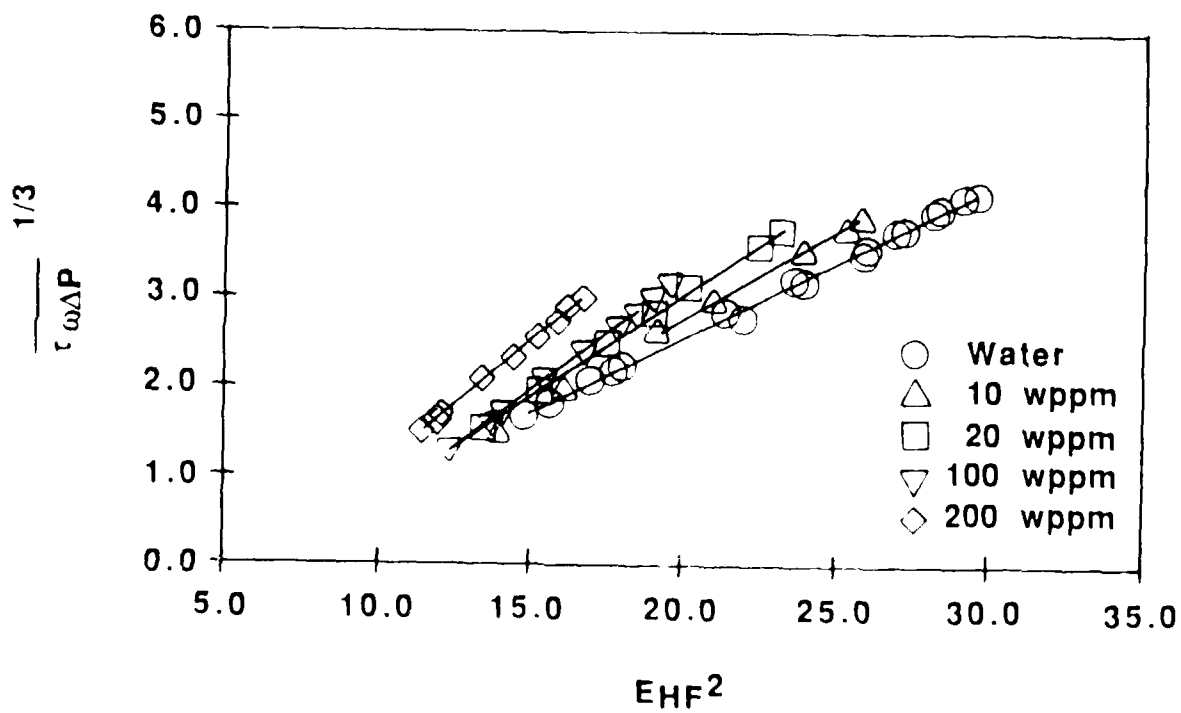Figure 6. Calibration Curves for the Downstream Hot-Film Using Separan AP-30 Solutions.
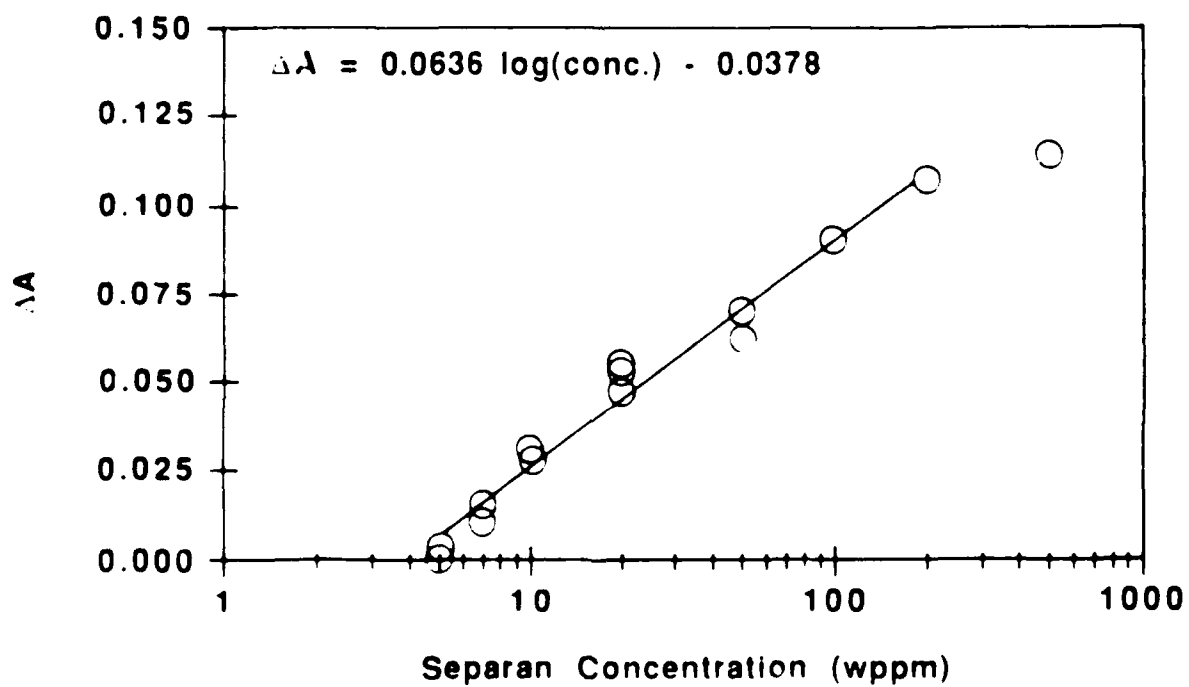
24

$$\Delta A = 0.0636 \log(\text{conc.}) - 0.0378$$

Figure :   Change in the Slop of the Hot-Film Calibration Curves as a
           Function of Polymer Concentration.

25

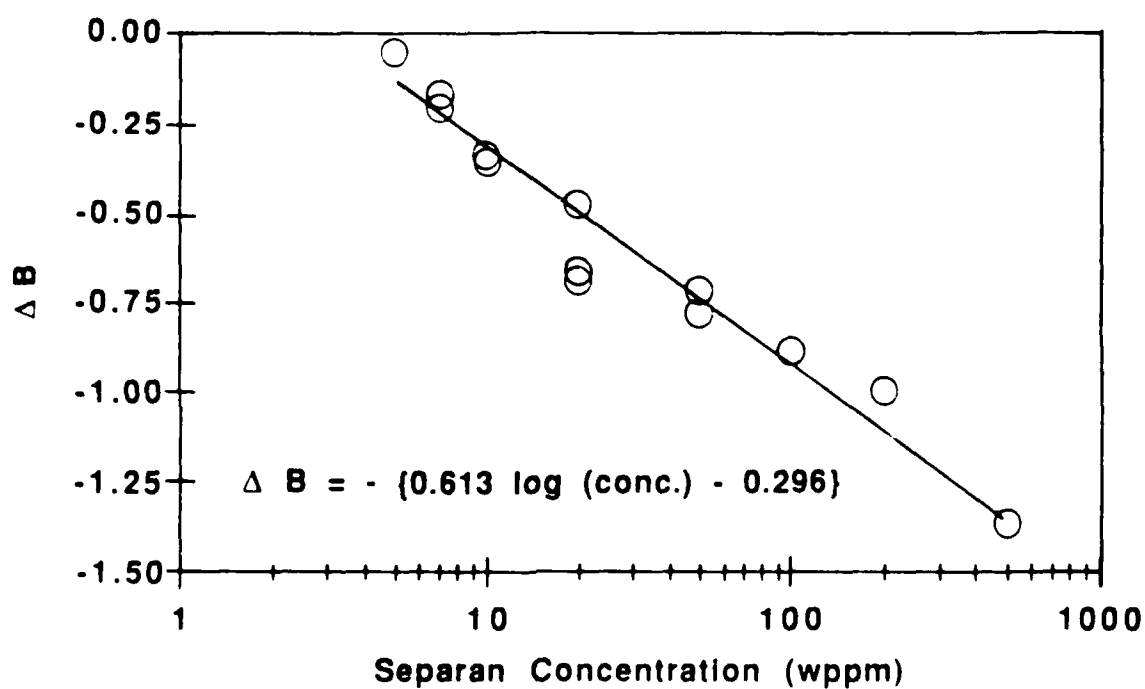$$\Delta B = - \{0.613 \log (\text{conc.}) - 0.296\}$$

Figure 8. Change in the Intercept of the Vertical Axis of the Hot-Film
Calibration Curves as a Function of Polymer Concentration.

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Evaluation of Flush Mounted Hot-Film Sensors For Skin Friction Reduction Measurements in Viscoelastic Polymer Solutions

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The performance of flush mounted hot-film sensors for mean wall shear stress measurement in turbulent flows of dilute drag reducing polymer solution is evaluated. A series of pipe flow experiments were conducted to compare the level of skin friction reduction measured by hot-film sensors with values determined from the pipe pressure drop. Water calibrated hot-film sensors consistently underestimate the wall shear stress in the dilute polymer flows. For the range of flows tested, hot-film determined percent drag reductions are low but generally within 15 percent of the correct value. Like drag reduction, heat transfer reduction results from the elastic properties of polymer solutions. These two phenomena are distinct and their differences suggest that Reynolds' analogy is not valid in the dilute polymer flows.

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